Draft version February 5, 2008
Preprint typeset using LaTeX style emulateapj v. 04/21/05

OBSERVATIONAL CONSTRAINTS ON THE AGES OF MOLECULAR CLOUDS AND THE STAR-FORMATION TIMESCALE: AMBIPOLAR-DIFFUSION–CONTROLLED OR TURBULENCE-INDUCED STAR FORMATION?

Telemachos Ch. Mouschovias, Konstantinos Tassis[1], and Matthew W. Kunz
Departments of Physics and Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, IL 61801
Draft version February 5, 2008

ABSTRACT

We revisit the problem of the star formation timescale and the ages of molecular clouds. The apparent overabundance of star-forming molecular clouds over clouds without active star formation has been thought to indicate that molecular clouds are "short-lived" and that star formation is "rapid". We show that this statistical argument lacks self-consistency and, even within the rapid star-formation scenario, implies cloud lifetimes ≈ 10 Myr. We discuss additional observational evidence from external galaxies that indicate lifetimes of molecular clouds and a timescale of star formation of $\approx 10^7$ yr. These long cloud lifetimes in conjunction with the rapid (≈ 1 Myr) decay of supersonic turbulence present severe difficulties for the scenario of turbulence-controlled star formation. By contrast, we show that all 31 existing observations of objects for which the linewidth, the size, and the magnetic field strength have been reliably measured are in excellent *quantitative* agreement with the predictions of the ambipolar-diffusion theory. Within the ambipolar-diffusion-controlled star formation theory the linewidths may be attributed to large-scale non-radial cloud oscillations (essentially standing large-amplitude, long-wavelength Alfvén waves), and the predicted relation between the linewidth, the size, and the magnetic field is a natural consequence of magnetic support of self-gravitating clouds.

Subject headings: ISM: clouds – magnetic fields – MHD – stars: formation – turbulence – waves

1. INTRODUCTION

The ages of molecular clouds and the timescale of star formation are currently at the center of an important debate in the field. However, the debate has a long history. Early on, Giant Molecular Clouds (GMCs) were believed to be very long-lived ($> 10^8$ yr) (Scoville *et al.* 1979). That estimate relied on two arguments. First, the distribution of CO emission in galactocentric coordinates lacked a clearly recognizable spiral pattern, indicating that GMCs are situated in both arm and interarm regions (Solomon *et al.* 1979). This implied that GMCs must be older than the rotational period of the Galaxy ($\simeq 10^8$ yr). Second, it was estimated that most of the interstellar hydrogen in the "molecular ring" (4-8 kpc) was molecular rather than atomic or ionic. Therefore the gas must spend most of its time in molecular form, which in turn implied GMC lifetimes greater than 10^8 yr.

Those early arguments for very long lifetimes of GMCs were refuted by Blitz & Shu (1980). They showed that the molecular-to-atomic hydrogen gas ratio was overestimated, while the random motions of the GMCs were neglected in the estimates of the kinematic distance, thereby leading to an erroneous spatial mapping. Furthermore, they presented a number of arguments that set the upper limit on the ages of GMCs at a few $\times 10^7$ yr.

It has recently been suggested that GMCs are short-lived ($\simeq 10^6$ yr), transient objects (Elmegreen 2000; Hartmann *et al.* 2001). The idea of short-lived molecular clouds has been thought to favor a scenario of turbulence-controlled star formation over the ambipolar-diffusion–controlled theory for two reasons. First, if the lifetime of GMCs is smaller than the ambipolar-diffusion timescale, then ambipolar diffusion does not have enough time to operate in molecular clouds and thus cannot be relevant to the star-formation process. Second, short cloud lifetimes help to circumvent the problem of rapid dissipation of supersonic turbulence and ease the energy requirements on the source(s) of turbulence, whatever that(those) might be.

The idea of short-lived molecular clouds is based on observational estimates of the ages of newborn stars in star forming regions and on molecular-cloud core statistics. These observations, however, were shown to be in excellent quantitative agreement with predictions of the ambipolar-diffusion theory for the timescales of the *observed* phases of star formation (Tassis & Mouschovias 2004; hereafter TM04). In this paper, we examine additional estimators of the ages of molecular clouds and of the star-formation timescale, and we present further observational evidence in favor of cloud lifetimes $\simeq 10^7$ yrs that has received little or no attention until now. We discuss the implications that cloud ages $\simeq 10^7$ yr have for current theories of star formation or for ideas on how the star-formation process is initiated. We also extend the work of Mouschovias & Psaltis (1995) and show that all 31 existing observations of objects (clouds, cores and even masers) for which the linewidth, the size, and the magnetic field strength have been reliably measured are in excellent quantitative agreement with the predicted relation between those three quantities, which is a natural and unavoidable consequence of magnetic support of self-gravitating clouds (Mouschovias 1987a).

2. CLOUD STATISTICS AND RAPID STAR FORMATION

[1] Current Address: Department of Astronomy and Astrophysics and the Kavli Institute for Cosmological Physics, 5640 South Ellis Avenue, University of Chicago, Chicago, IL 60637

The timescale of star formation derived from estimates of the ages of protostars and the age spreads of stars in clusters was shown by TM04 to reflect only the late stages of star formation, after the creation of an opaque hydrostatic core, and ignores a potentially long earlier phase. However, the existence of an appreciably long phase before the appearance of a hydrostatic protostellar core implies that molecular clouds spend a significant part of their lives without observable embedded protostars. If that is the case, a significant fraction of molecular clouds should be observed to contain no protostars. Yet, most molecular clouds are observed to have embedded protostars. It is thus claimed that the statistics of molecular clouds with and without protostars is at odds with the picture presented by TM04 (Klessen *et al.* 2005).

First, it cannot be overemphasized that the duration of this starless phase, which is essentially the time it takes ambipolar diffusion to form a magnetically (and thermally) supercritical, dynamically-contracting core (or, fragment) from the mean density of an initially magnetically subcritical molecular cloud, is not a universal number – although it is often used as if it were such. It depends: (1) on the factor by which the initial central mass-to-flux ratio of the parent cloud is smaller than its critical value for collapse (Mouschovias & Spitzer 1976; Mouschovias 1991a; Fielder & Mouschovias 1993; Ciolek & Basu 2001); and (2) on the (initial) degree of ionization of the parent cloud (Mouschovias 1979, 1987a, 1996). These two quantities are *observational input* to, not predictions of, the theory. The duration of the subcritical phase of core formation and contraction can be as short as 1 Myr for mildly subcritical clouds, and as long as 10 Myr for strongly subcritical clouds. The ambipolar-diffusion theory does *not* predict *nor* require strongly magnetically subcritical clouds. Therefore, it does not require lifetimes of molecular clouds of the order of 10 Myr in order to be relevant for star formation. For these reasons, the ambipolar-diffusion theory of star formation does *not* require molecular clouds to spend most of their lifetimes in a starless state although, if this turns out to be the case, the theory can definitely accommodate and explain such an observation.

Second, the claim that most observed clouds contain protostars is based on a very biased and incomplete list of molecular clouds (those in the solar neighborhood). If molecular-cloud formation is triggered by a spiral density shock wave, as envisioned by Mouschovias *et al.* (1974), and as evidenced by the appearance of young, bright OB stars downstream from the galactic shock (Morgan 1970), then young molecular clouds without embedded stars should be found behind the galactic shock, which is traced (in external galaxies) by dust lanes and a sharp peak of HI emission. As one observes matter farther away from the shock *across* a spiral arm, one should see older clouds that begin to give birth to stars. This picture is indeed confirmed by observations of external galaxies seen face-on (see § 3 below). In the Milky Way, such surveys across spiral arms are difficult, if not impossible, to perform. Instead, surveys of molecular clouds in the Milky Way are biased toward active regions of star formation.

Third, even if we were to accept the observations in the solar neighborhood on which this claim is based as representative, they do not support the idea of "young" molecular clouds. If $\tau_{\rm SF}$ is the star-formation timescale and $\tau_{\rm MC}$ the molecular-cloud lifetime, then the statistical argument implies that

$$\frac{\tau_{\rm SF}}{\tau_{\rm MC}} = \frac{N_{\rm NS}}{N_{\rm total}}\,, \tag{1}$$

where $N_{\rm NS}$ is the number of molecular clouds with *N*o *S*tars, and $N_{\rm total}$ is the total number of observed clouds. (Note: For $t \leqslant \tau_{\rm SF}$, no cloud contains any stars. If $\tau_{\rm SF} > \tau_{\rm MC}$, the clouds will disperse before they form stars; hence, $N_{\rm NS} = N_{\rm total}$. If $\tau_{\rm SF} \approx \tau_{\rm MC}$, the clouds will disperse just as they are ready to form stars; hence, $N_{\rm NS} \approx N_{\rm total}$. Eq. [1] holds for $\tau_{\rm SF} \leqslant \tau_{\rm MC}$.) In the "rapid" star-formation scenario, $\tau_{\rm SF} \simeq 1\,{\rm Myr}$ (Vázquez-Semadeni *et al.* 2005). Then, if $N_{\rm NS}/N_{\rm total} \simeq 0.1$, as it has been claimed, equation (1) yields $\tau_{\rm MC} \simeq 10\,{\rm Myr}$, and the clouds are *not* young. Note that the smaller the $N_{\rm NS}/N_{\rm total}$ ratio, the greater the estimated lifetime of molecular clouds, as given by this statistical argument! However, such a scenario (small $\tau_{\rm SF}$ and large $\tau_{\rm MC}$) is contradicted by observations of age spreads of young stars in star-forming regions, which are found to be a few Myr (e.g., Sung *et al.* 1998; Baume *et al.* 2003). Hence, the "rapid" star formation scenario lacks internal consistency.

A recent, independent line of reasoning (Goldsmith & Li 2005), that relies on the measured atomic-hydrogen content of molecular clouds to estimate the clouds' ages, lends support to lifetimes $\gtrsim 10^7$ yr.

3. EVIDENCE FOR THE STAR-FORMATION TIMESCALE IN EXTERNAL GALAXIES

W. W. Roberts (1967) first suggested that galactic shock waves traced by dust lanes and the sharp HI emission peak may provide the triggering mechanism for star formation and thus newborn stars should be located downstream at a distance implied by the timescale for star formation and the rotational speed of the gas relative to the spiral pattern. Early on, M. S. Roberts (1967) showed that the circumferential bands with highest HI distribution in a number of spiral galaxies lie significantly outside the bands of the optical arms containing the most prominent newly-born stars and HII regions.

In M51, Mathewson *et al.* (1972) did a radio continuum survey at 450 pc linear resolution at the distance of M51. They found the peak of radio intensity to coincide with the dust lanes, at the inner edge of spiral arms, but they detected a lag with respect to the position of the bright young stars. With respect to the galaxy's center, the spiral arms delineated by the radio emission and the spiral arms delineated by the HII regions have a difference of 18° in position angle, at a distance R from the galactic center. This corresponds to a linear separation of

$$L = 2R \sin\frac{18^\circ}{2} = 0.31R\,. \tag{2}$$

From this linear separation, they calculated the time it takes the gas to reach the position of the bright stars after it encounters the galactic shock, and they found that the star-formation timescale is

$$\tau_{\rm SF} = \frac{L}{v_{\rm d}} = 6\times10^6 \left(\frac{D}{4\,{\rm Mpc}}\right)\left(\frac{100\,{\rm km\,s^{-1}}}{v_{\rm d}}\right)\ \ {\rm yr}\,, \tag{3}$$

where v_{d} is the difference between the rotation speeds of the gas and the spiral pattern. Using the updated value for the distance of M51, $D = 8.4\,\mathrm{Mpc}$ (Feldmeier *et al.* 1997), equation (3) yields

$$\tau_{\mathrm{SF}} = 12.5\,\mathrm{Myr}\,. \tag{4}$$

This shift between CO and Hα peaks was also observed by Vogel *et al.* (1988) and by Rand & Kulkarni (1990). More recently, the molecular content of M51 was studied by García-Burillo *et al.* (1993) with the IRAM 30m telescope. Their resolution was about 560 pc at the distance of M51 (they adopted a distance of 9.6 Mpc, from Sandage & Tamman 1975). The spiral arms are prominently traced by CO with the peak emission being located at the dust lanes, coincident with the nonthermal radio emission peak, and is separated from the Hα peak by a distance corresponding to the aforementioned timescale $> 10^7$ yr. The density of the molecular gas was estimated from the intensity ratio of the J=2−1 and J=1−0 CO emission to be typical of GMCs.

Similarly in M81, Rots (1975) found a phase difference 10° to 15° between the blue dips in the optical spiral arms and the peaks of HI surface density. Using a speed of 20 km s^{-1} kpc^{-1} for the spiral pattern and an average radius of 5 kpc, he estimated the time lag to be approximately 10 Myr.

4. IMPLICATIONS FOR STAR FORMATION THEORIES

Given the arguments above and in TM04 against short-lived ($\simeq$ 1 Myr) molecular clouds, it is natural to ask where star formation theory stands in this regard. It has long been known that molecular clouds exhibit supersonic linewidths (see review by Zuckerman & Palmer 1974), which are inextricably linked to how such dense ($n \simeq 10^3$ cm^{-3}), cold ($T \simeq 10$ K) objects, whose masses are typically 10^2 to 10^4 greater than the thermal (or Jeans, or Bonnor-Ebert) critical mass, could be supported against their self-gravity, or whether they are supported at all. Possible explanations for the linewidths are radial collapse (or expansion) (Shu 1973; Liszt *et al.* 1974; Goldreich & Kwan 1974; Scoville & Solomon 1974), random motions of clumps within clouds (Zuckerman & Evans 1974; Morris *et al.* 1974), supersonic turbulence (Larson 1981; Leung *et al.* 1982; Myers 1983), and hydromagnetic waves (Arons & Max 1975; Mouschovias 1975; Zweibel & Josafatsson 1983). The first two possibilities have long been ruled out (Zuckerman & Evans 1974; Mouschovias 1975), while there still exists a debate over the latter two. Regardless of one's opinion, a common task is at hand: how to maintain the motions responsible for the large linewidths over a cloud's lifetime ($\simeq$ 10 Myr). Any explanation has direct implications for cloud structure and evolution and, hence, for theories of star formation.

4.1. *Turbulence-Induced Star Formation*

When Larson (1981) compiled data on linewidths of 54 clouds, clumps, and cores, and found a relation between the observed velocity dispersion σ_{v} and the size (diameter) L of each object (the so-called "turbulence law" $\sigma_{\mathrm{v}} \propto L^{0.38}$, which was thought to be the signature of Kolmogorov turbulence), supersonic turbulence appeared to be a natural explanation. Subsequent work by Leung *et al.* (1982) and Myers (1983) also found a power-law relation, albeit with a significantly greater exponent, $\simeq 0.5$. Due in part to the influence of Larson's original work, it is widely believed even today that the characteristic scaling relations at the heart of theories of turbulence may still provide the most natural explanation of the linewidth-size relation (Myers & Gammie 1999).

It is well known that supersonic turbulence decays very rapidly ($\lesssim$ 1 Myr) and has very high energy requirements (Mestel & Spitzer 1956; Field 1970, 1973). Moreover, relatively recent numerical simulations (Stone, Ostriker, & Gammie 1998; Mac Low *et al.* 1998; Ostriker *et al.* 1999; Padoan & Nordlund 1999; Ostriker *et al.* 2001) show that magnetic fields cannot mediate the decay of such turbulence (often assumed to be initially superAlfvénic, although such an assumption lacks observational support; see below).

In light of the arguments for long lifetimes of molecular clouds, this relatively rapid decay poses a serious problem for the turbulence-induced star formation idea, that assumes that turbulence alone is responsible for suppressing global cloud collapse while allowing local collapse to occur in turbulence-produced cores. A suitable driving mechanism that can replenish the rapidly-decaying turbulence is required.

Both internal and external driving mechanisms have been considered as means for replenishing the turbulence. Possible candidates for internal driving are stellar winds, bipolar outflows, and HII regions. However, there exist molecular clouds devoid of visible star formation that exhibit a higher level of turbulence than clouds with embedded OB associations (McKee 1999). Besides, a theory of star formation must be able to explain how the first stars form in a molecular cloud, without having to rely on possible *stellar* triggers. These arguments, along with results from simulations of driven cloud turbulence (Ossenkopf & Mac Low 2002; Klessen *et al.* 2005), have led to the realization that internal driving cannot be reconciled with observations of actual molecular clouds. As a result, attention is now turning to external driving mechanisms, which include supernovae, density waves, differential rotation of galactic disks, and winds from massive stars.

External driving of supersonic turbulence has its own serious difficulties:

1. Inward propagating disturbances (compressible turbulence) impart linear momentum to the matter in their direction of propagation, thereby tending to aid the self-gravity of a cloud in inducing collapse (Mouschovias 1987a). Consequently, a mechanism other than turbulence must exist and be responsible for the support of self-gravitating clouds.

2. The material motions (e.g., shocks) implied by the inward propagating, nonlinear disturbances ($\simeq 1\,\mathrm{km\,s^{-1}}$) even in clouds that have not yet given birth to stars are not observed in molecular clouds.

3. External driving from supernovae (or the winds of massive stars), which are currently considered to be the most promising external source of turbulent energy (Klessen *et al.* 2005), assumes that stars in the neighborhood of a cloud under study have formed by means unrelated to turbulence. If star formation can take place in other clouds without any assistance from turbulence,

there is no reason to postulate that the same mechanism responsible for that star formation cannot operate in the cloud under consideration.

Regardless of the possible sources of supersonic turbulence or any role that such turbulence may or may not play in the structure and evolution of molecular clouds, the linewidth-size relation that was a key motivation for invoking such turbulence in the first place has not been adequately explained by numerical simulations of turbulence (see § 5.2 in Elmegreen & Scalo 2004 for a discussion of the wide range of conflicting results on linewidth-size relations from different numerical studies).

4.2. *Ambipolar-Diffusion–Initiated Star Formation*

4.2.1. *Theory vs. Observations*

The role of cosmic magnetic fields in the formation and support of self-gravitating clouds and the formation and evolution of protostars in such clouds has been synthesized into the theory of ambipolar-diffusion–initiated star formation, based on detailed analytical and numerical work over the last thirty years (see reviews by Mouschovias 1978, 1981, 1987a, 1987b, 1995, 1996; Mouschovias & Ciolek 1999). In this theory, the formation of self-gravitating cloud cores (or fragments) and their evolution into protostars is a result of the incessant struggle between gravitational forces and their principal opponent, magnetic forces, with ambipolar diffusion being the clever means by which gravity eventually wins that battle.

The outcome of this struggle is determined mainly by the initial mass-to-flux ratio, $M/\Phi_{\rm B}$, and the initial degree of ionization, $x_{\rm i} \equiv n_{\rm i}/n_{\rm n}$, of the parent *cloud.* These quantities are not predictions of the theory; they are *observational input* to the theory. (However, the theory makes definite predictions about the mass-to-flux ratio of molecular cloud *cores*; namely, it should typically be supercritical by a factor 1 - 3 for cores with central density $\simeq 10^5 - 10^9\,{\rm cm}^{-3}$; e.g., see Fiedler & Mouschovias 1993, Fig. 9b. This prediction is in excellent agreement with all observations of mass-to-flux ratios in cloud cores to date [Crutcher 1999; Crutcher *et al.* 2004; Heiles & Crutcher 2005]. For the effect of rotation and/or grains on this prediction, see, respectively, Basu & Mouschovias 1994, Fig. 8b; Ciolek & Mouschovias 1994, Fig. 4e.) Ambipolar diffusion leads to *quasistatic* (i.e., negligible acceleration, but not necessarily negligible velocity) formation of magnetically supercritical cores in the deep interiors of molecular clouds followed by their *dynamic* contraction (collapse, but not free fall). The envelope of the parent molecular cloud remains magnetically supported. The theory predicts ordered large-scale magnetic fields with hourglass morphology and with strength B in the cores that is related to their density ρ by $B \propto \rho^\kappa$, where $\kappa = 0.47$. Thermal pressure forces are primarily responsible for maintaining a nearly uniform density in the central region, while the density decreases approximately as $\rho \propto r^{-2}$ in a region $r \approx 10^2 - 10^4$ AU, the dynamically contracting (but not free-falling), thermally and magnetically supercritical core. (This structure is distinct from Shu's [1977] singular isothermal sphere model of low-mass [a few solar masses] clouds, in which the r^{-2} density profile refers to the *static* cloud envelope, the dynamically contracting inner region has a $r^{-1.5}$ profile, and there is no flat-density central region.) Turbulence is not required for cloud support (although, if present, it is accommodated in the theory), so the problem of its rapid decay is irrelevant to the ambipolar-diffusion theory of star formation.

Observations of molecular clouds confirm many of the predictions of the ambipolar-diffusion theory and, just as importantly, contradict none. The envelopes of molecular clouds are subcritical (or critical), whereas cloud cores are supercritical (Crutcher *et al.* 1993, 1994, 1996, 2004; Heiles & Crutcher 2005; Cortes *et al.* 2005). Large-scale ordered fields, often with hourglass morphology, are seen threading the clouds (Vrba *et al.* 1981; Schleuning 1998; Lai *et al.* 2002) and their cores. Low-mass cores are found in the deep interiors of clouds, rather than near the surface (Johnstone *et al.* 2004). The observed scaling relation between B and ρ has $\kappa = 0.47 \pm 0.08$ (Crutcher 1999). Millimeter and submillimeter continuum observations by Ward-Thompson *et al.* (1994) and André *et al.* (1996) yield density profiles for starless cores that are in excellent agreement with those predicted by the ambipolar-diffusion theory. Ion-neutral drift speeds have been measured by Benson *et al.* (1998) and found consistent with the theory. Specific dynamical models have been constructed for the Barnard B1 cloud (Crutcher *et al.* 1994) and L1544 (Ciolek & Basu 2000a) and have predicted core properties that are in excellent agreement with observations. Ciolek & Basu (2000b) discuss further the close agreement between the ambipolar-diffusion theory and observations. By contrast, *quantitative* agreement between observations and the results of simulations resulting in presumed initiation of fragmentation (or core formation) by turbulence in molecular clouds is lacking.

Two points must be made regarding the mass-to-flux ratio. First, statistical arguments have been offered (e.g., Crutcher 1999) to the effect that clouds are supercritical, in presumed contradiction to the ambipolar diffusion theory. However, all observations on which that deduction is made are based on measurements of the magnetic field strength in *cores.* As explained above, the definite prediction of the ambipolar-diffusion theory has been that typical cores *must* be nearly critical or slightly supercritical. Hence, the criticism of the ambipolar-diffusion theory on the basis of observed mass-to-flux ratios rests on a fundamental misunderstanding of the theory. [2]

Second, there is an important distinction between the ambipolar-diffusion theory of star formation and the idea of turbulence-driven star formation as they relate to the mass-to-flux ratio. The theory of ambipolar-diffusion–initiated star formation predicts tight constraints on how the mass-to-flux ratio should vary between a cloud envelope and its cores (see above). Turbulence-driven fragmentation, on the other hand, predicts $M/\Phi_{\rm B} \gg (M/\Phi_{\rm B})_{\rm crit}$ to be as equally likely as

[2] This confusion has found its way into recent papers [e.g., Mac Low & Klessen (2004), Li *et al.* (2004)] that criticize the ambipolar-diffusion theory on the grounds that (1) magnetic clouds *as a whole* are observed to be supercritical, and (2) the ambipolar-diffusion theory predicts subcritical cores, *neither of which is true.* Similar misinterpretation of observational data has also led to simulations of supercritical molecular clouds, sometimes with mass-to-flux ratios an order of magnitude supercritical (Li *et al.* 2004). Such a large mass-to-flux ratio has never been observed in molecular clouds.

$M/\Phi_{\rm B} \approx (M/\Phi_{\rm B})_{\rm crit}$ in *both* molecular cloud cores *and* their envelopes. Observations show that this is not the case (e.g., see Heiles & Crutcher 2005).

4.2.2. *Explanation of the Linewidths*

Magnetic support of molecular clouds has led to a natural explanation of the observed linewidths, without any *ad hoc* assumptions. If (1) self-gravitating clouds are magnetically supported, and (2) the material velocities responsible for the supersonic linewidths are slightly sub-Alfvénic or Alfvénic [i.e., $(\Delta v)_{\rm NT} \simeq (\Delta v)_{\rm wave} \lesssim v_{\rm A}$], then the linewidths may be attributed to large-scale non-radial cloud oscillations, which are essentially *standing* large-amplitude, long-wavelength ($\lambda \simeq 1$ pc) Alfvén waves. The predicted nonthermal linewidth $(\Delta v)_{\rm NT}$ is related to the magnetic field strength B and the size R of the object by

$$(\Delta v)_{\rm NT} \simeq 1.4 \left(\frac{B}{30\ \mu{\rm G}}\right)^{1/2} \left(\frac{R}{1\ {\rm pc}}\right)^{1/2} \quad {\rm km\ s^{-1}} \qquad (5)$$

(Mouschovias 1987a; Mouschovias & Psaltis 1995). Equilibrium oscillations left over from the cloud formation process (Mouschovias 1975; Galli 2005) could be the origin of these waves. They decay on the ambipolar-diffusion timescale.

That the linewidths should be slightly sub-Alfvénic or Alfvénic is suggested by the work of Mouschovias & Morton (1985a,b), who found that equipartition is established between the magnetic energy in Alfvén waves and the kinetic energy of the material motions associated with the waves after only a few reflections off fragments (or the cloud surface) and the consequent wave-wave interaction. Observations of linewidths confirmed that prediction (Myers & Goodman 1988; Crutcher 1999). SuperAlfvénic linewidths have *never* been observed in self-gravitating molecular clouds; this has particularly devastating consequences for star formation ideas that require superAlfvénic turbulence in order for simulations to match observed characteristics of clouds (e.g., Padoan & Nordlund 1999; Li *et al.* 2004).

Equation (5) was shown by Mouschovias & Psaltis (1995) to be in excellent quantitative agreement with spectral line observations of clouds, cores, and embedded OH masers; they considered the 14 objects for which the linewidth, size, and magnetic field strength were measured at the time. By now there are 31 sources for which all three quantities [$(\Delta v)_{\rm NT}$, size R, and field strength B] have been reliably measured (Myers & Goodman 1988; Crutcher 1999; Crutcher *et al.* 2004). The total magnetic field strength B is taken to be the usual statistical average over inclination angles: $B = 2|B_{\rm los}| = 4|B_{\rm sky}|/\pi$ (where $B_{\rm los}$ and $B_{\rm sky}$ are the components of the field along the line-of-sight and in the plane of the sky, respectively) for clouds and cores, and $B = |B_{\rm los}|$ for masers.

We use this data to plot $(\Delta v)_{\rm NT}$ versus R in Figure 1a. Error bars are as in Myers & Goodman (1988); they indicate an uncertainty of a factor of 2. No single power law can meaningfully fit the data, in that the standard deviation would be too large. In Figure 1b we separate these points into weak-field ($B \leq 270$ μG; open circles), moderate-field (270 μG $< B <$ 3000 μG; grey circles), and strong-field (3000 μG $\leq B$; black circles)

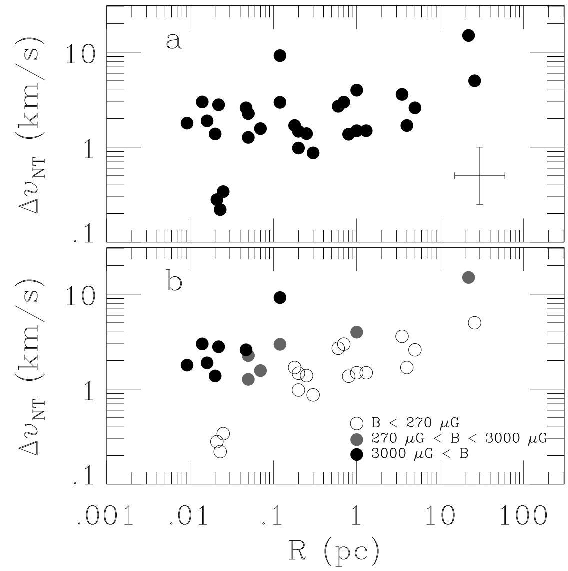

FIG. 1.— (a) Nonthermal linewidth vs. (FWHM) size for 31 objects (data from Myers & Goodman 1988; Crutcher 1999; and Crutcher *et al.* 2004). (b) Same linewidth-size data as in (a), but grouped according to the total magnetic field strength (see text for definition of B).

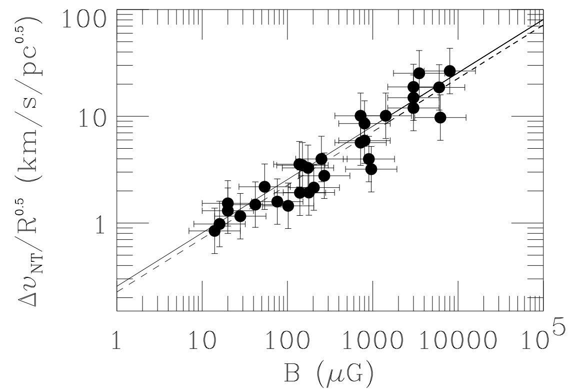

FIG. 2.— Same linewidth-size data as in Fig. 1, but exhibiting the ratio $(\Delta v)_{\rm NT}/R^{1/2}$ as a function of the total magnetic field strength B. Error bars are as in Fig. 1. The theoretical prediction (eq. [5]) is shown as a solid line. The dashed line is a least-squares fit to the data.

regimes. There is a clear indication that sources of different magnetic-field strength follow different scaling laws. In Figure 2, we show the same data, but we plot the quantity $(\Delta v)_{\rm NT}/R^{1/2}$ against B. Error bars are as in Figure 1. The solid line is the theoretical prediction, equation (5). The dashed line is a least-squares fit to the data. The quantitative agreement between theory and observations is remarkable. The theoretical prediction and the least-squares fit have exactly the same slope. In addition, the fact that the theoretical prediction is offset slightly higher than the least-squares fit indicates that the material motions responsible for the linewidths are slightly subAlfvénic.

Attributing the linewidths to standing, large-amplitude, long-wavelength Alfvén waves does not affect the evolution of a protostellar core in any way. For typical molecular cloud parameters, the size of the region that can just become gravitationally unstable because of ambipolar diffusion happens to be essentially equal to the Alfvén lengthscale $\lambda_{\rm A}$ (Alfvén waves with wave-

lengths $\lambda \leq \lambda_A$ cannot propagate in the neutrals because of damping by ambipolar diffusion — see Mouschovias 1991b, eqs. [18a,b]). In fact, it is precisely the decay of hydromagnetic waves due to ambipolar diffusion that removes part of the support against gravity over the critical thermal lengthscale and thus initiates fragmentation (or core formation) in molecular clouds (Mouschovias 1987a). One should therefore expect thermalization of linewidths on the Alfvén lengthscale in supercritical cores. This has been observed by Bacmann *et al.* (2002) in L1544.

5. DISCUSSION

In this paper, we have re-examined the argument that an observed overabundance of molecular clouds that are actively forming stars with respect to clouds without active star formation indicates that molecular clouds are "short-lived" and that star formation is "rapid". According to that argument, ambipolar diffusion does not have enough time to operate in molecular clouds. We have shown that: (a) Even if the observational facts used to support that argument were unbiased and accurate, these statistics imply molecular cloud lifetimes $\simeq 10$ Myr, even within the "rapid" star-formation scenario. (b) Observations of molecular clouds in the solar neighborhood are *not* in fact unbiased or representative — rather, quiescent clouds are expected to be found mostly close to a galactic shock along spiral arms, as is observed in external, face-on spiral galaxies. (c) The ambipolar-diffusion theory of star formation does *not* require long quiescent periods of molecular clouds or cloud lifetimes $\gtrsim 10$ Myr, although it can certainly explain and accommodate such a possibility. Furthermore, if molecular clouds were short-lived, "transient", "evanescent", nongravitating structures (Elmegreen 2000; Hartmann *et al.* 2001), then they should be dispersing fast, in $\simeq 1$ Myr. This implies that molecular clouds with embedded protostars should exhibit large, (ordered) expansion velocities. Such velocities are *not* observed. [3]

We have also examined the implications of these results for star-formation theories or ideas. Theories or ideas that depend on supersonic, magnetized or nonmagnetized turbulence for fragmentation, core formation, and cloud support are burdened by the requirement of continuously replenishing the turbulent motions during the entire lifetime of a molecular cloud. Proponents of this idea have found that internal driving of the turbulence cannot be reconciled with observations of actual molecular clouds. We have argued that external driving will most likely result in cloud compression and premature collapse. Also, the most promising external driving mechanisms (e.g., supernovae and winds from massive stars) assume the pre-existence of stars, and do not explain the origin of that previous generation of stars. Furthermore, recent observations (Koda *et al.* 2005), which find molecular clouds to be preferentially elongated along the Galactic plane, are in conflict with driving by supernovae and stellar winds, since these cannot account for the preferred elongation. Without an adequate source of driving, the observed supersonic linewidths cannot be maintained over a cloud's lifetime. Moreover, the linewidth-size relation first established by Larson (1981) and extended by Leung *et al.* (1982) and Myers (1983), which was a key motivation for invoking turbulence in the first place, has not been explained by current numerical simulations of molecular cloud turbulence. Since superAlfvénic linewidths have never been observed in self-gravitating molecular clouds, turbulent star formation ideas that require superAlfvénic turbulence in order for their simulations to match observed cloud properties (e.g, Padoan & Nordlund 1999; Li *et al.* 2004) have no relevance to actual molecular clouds.

By contrast, the theory of ambipolar-diffusion–initiated star formation has, over the last thirty years, made numerous *quantitative* predictions that turned out to be in excellent agreement with observations. Cloud envelopes are supported by magnetic fields while ambipolar diffusion allows supercritical cores to form and dynamically collapse in the deep interiors of self-gravitating clouds. This is supported by detailed numerical simulations as well as by polarimetry and Zeeman observations. The linewidths are due to nonradial cloud oscillations, which are essentially standing large-amplitude, long-wavelength Alfvén waves. Linewidth, size, and magnetic field data from 31 clouds, cores, and embedded masers are in excellent quantitative agreement with this theory. The theory does not suffer from a need to replenish turbulent motions in order to support clouds against collapse or to explain the linewidths, although if such replenishment takes place it has no effect on the ambipolar-diffusion theory of fragmentation and star formation: ambipolar diffusion damps the waves precisely over the lengthscales necessary for gravitational formation and contraction of fragments (or cores) (see Mouschovias 1987a, 1991).

We caution against using mass-to-flux ratios from observations of molecular cloud cores to make statements about the mass-to-flux ratios of molecular cloud envelopes. Supercritical cloud cores are a prediction of the ambipolar-diffusion–initiated star formation theory, and do not imply that magnetic support is insignificant in the envelopes. Moreover, the fact that observed cloud cores are critical or slightly supercritical and cloud envelopes are subcritical contradicts the simulations of turbulence-induced star formation, whose results imply that highly supercritical cores are equally likely as slightly supercritical cores.

It is important to clarify the semantic difference between "rapid" and "slow" star formation. When one refers to a process as being rapid or slow, one must also specify with respect to what. The main theoretical motivation for pursuing the idea of "short-lived" molecular clouds was to test whether ambipolar diffusion has enough time to operate and form supercritical cores over the lifetime of a molecular cloud. We have once again pointed out that the timescale of the ambipolar-diffusion–controlled core formation process depends on the mass-to-flux ratio and the degree of ionization of the parent cloud and it can be as short as 1 Myr for mildly subcritical clouds. Hence, from this perspective, clouds

[3] Even if it *were* the case that all molecular clouds had embedded stars, the conclusions one would draw within the ambipolar-diffusion theory would be: (1) The cloud ages are longer than the star-formation timescale. (2) The ambipolar-diffusion timescale in every molecular cloud is smaller than the cloud's lifetime. (3) Molecular clouds formed at about the same time (behind a spiral density shock wave). Consequently, statistical arguments cannot be applied to such clouds.

with ages of a few Myr are not "young" enough to render the ambipolar diffusion theory irrelevant to star formation. Loose terminology should not replace quantitative standards for determining the validity of a theory.

Acknowledgments: This work has been carried out without external support, and this paper would not have been published without the generosity of *The Astrophysical Journal*.

REFERENCES

André, P., Ward-Thompson, D., & Motte, F. 1996, A&A, 314, 625
Arons J., & Max C. E. 1975, ApJ, 196, L77
Bacmann, A., Andre, P., Puget, J.-L., Abergel, A., Bontemps, S. & Ward-Thompson, D. 2002, A&A, 361, 555
Basu, S., & Mouschovias, T. Ch. 1994, ApJ, 432, 720
Baume, G., Vázquez, R. A., Carraro, G. & Feinstein, A. 2003, A&A, 402, 549
Benson, P.J., Caselli, P., & Myers, P. C. 1998, ApJ, 506, 743
Blitz, L., & Shu, F. H. 1980, ApJ, 238, 148
Ciolek, G. E., & Basu, S. 2000a, ApJ, 529, 925
Ciolek, G. E., & Basu, S. 2000b, in *From Darkness to Light: Origin and Evolution of Young Stellar Clusters*, ASP Conference Proceedings, ed. T. Montmerle & P. André (San Francisco: ASP), 243, 79
Ciolek, G. E., & Basu, S. 2001, ApJ, 547, 272
Ciolek, G. E., & Mouschovias, T. Ch. 1994, ApJ, 425, 142
Cortes, P. C., Crutcher, R. M., & Watson, W. D. 2005, astro-ph/0504258
Crutcher, R. M. 1999, ApJ, 520, 706
Crutcher, R. M., Mouschovias, T. Ch., Troland, T. H., & Ciolek, G. E. 1994, ApJ, 427, 839
Crutcher, R. M., Nutter, D. J., Ward-Thompson, D., & Kirk, J. M. 2004, ApJ, 600, 279
Crutcher, R. M., Roberts, D. A., Mehringer, D. M., & Troland, T. H. 1996, ApJ, 462, L79
Crutcher, R. M., Troland, T. H., Goodman, A. A., Heiles, C., Kazés, I., & Myers, P. C. 1993, ApJ, 407, 175
Elmegreen, B. G. 2000, ApJ, 530, 277
Elmegreen, B. G., & Scalo, J. 2004, ARA&A, 42, 211
Feldmeier, J. J., Ciardullo, R., & Jacoby, G. H. 1997, ApJ, 479, 231
Fiedler, R. A., & Mouschovias, T. Ch. 1993, ApJ, 415, 680
Field G. B. 1970, in *Interstellar Gas Dynamics*, ed. H.J. Habing (Dordrecht: Reidel), 51
Field G. B. 1973, in *Molecules in the Galactic Environment*, ed. M. A. Gordon & L. E. Snyder (New York: Wiley-Interscience), 21
Galli, D. 2005, astro-ph/0502584
García-Burillo, S., Guélin, M., & Cernicharo, J. 1993, A&A, 274, 123
Goldreich, P., & Kwan, J. 1974, ApJ, 189, 441
Goldsmith, P. F., & Li, D. 2005, ApJ, 622, 938
Hartmann, L., Ballesteros-Paredes, J., & Bergin, E. A. 2001, ApJ, 562, 852
Heiles, C. & Crutcher, R. 2005, astro-ph/0501550
Johnstone, D., Di Francesco, J., & Kirk, H. 2004, ApJ, 611, 1
Klessen, R. S., Ballesteros-Paredes, J., Vázquez-Semadeni, E., & Durán-Rojas, C. 2005, ApJ, 620, 786
Koda, J., Sawada, T., Hasegawa, T., & Scoville, N. 2005, astro-ph/0510201
Lai, S. P., Crutcher, R. M., Girart, J. M., & Rao, R. 2002, ApJ, 566, 925
Larson, R. B. 1981, MNRAS, 194, 809
Leung, C. M., Kutner, M. L., & Mead, K. N. 1982, ApJ, 262, 583
Li, P. S., Norman, M. L., Mac Low, M-M., & Heitsch, F. 2004, ApJ, 605, 800
Liszt, H. S., Wilson, W. W., Penzias, A. A., Jefferts, K. B., Wannier, P. G., & Solomon, P. M. 1974, ApJ, 190, 557
Mac Low, M.-M., & Klessen, R. S. 2004, RvMP, 76, 125
Mac Low, M.-M., Klessen, R. S., Burkert, A., & Smith, M. D. 1998, Phys. Rev. Lett., 80, 2754
Mathewson, D. S., van der Kruit, P. C., & Brouw, W. N. 1972, A&A, 17, 468
McKee, C. F. 1999, in *The Origin of Stars and Planetary Systems*, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 29
Mestel, L., & Spitzer, L., Jr. 1956, MNRAS, 116, 503
Morgan, W. W. 1970, in *The Spiral Structure of Our Galaxy*, IAU Symp. No.38, 9
Morris, M., Zuckerman, B., Turner, B. E., & Palmer, P. 1974, ApJ, 192, L23
Mouschovias, T. Ch. 1975, Ph.D. thesis, Univ. California, Berkeley
Mouschovias, T. Ch. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: Univ. Arizona Press), 209
Mouschovias, T. Ch. 1979, ApJ, 228, 475
Mouschovias, T. Ch. 1981, in *Fundamental Problems in the Theory of Stellar Evolution*, ed. D. Sugimoto, D. Q. Lamb, & D. N. Schramm (Dordrecht: Reidel), 27
Mouschovias, T. Ch. 1987a, in *Physical Processes in Interstellar Clouds*, ed. G. E. Morfill & M. Scholer (Dordrecht: Reidel), 453
Mouschovias, T. Ch. 1987b, in *Physical Processes in Interstellar Clouds*, ed. G. E. Morfill & M. Scholer (Dordrecht: Reidel), 491
Mouschovias, T. Ch. 1991a, in *The Physics of Star Formation and Early Stellar Evolution*, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 449
Mouschovias, T. Ch. 1991b, ApJ, 373, 169
Mouschovias, T. Ch. 1995, in *The Physics of the Interstellar Medium and Intergalactic Medium*, ed. A. Ferrara, C. F. McKee, C. Heiles, & P. R. Shapiro (San Francisco: ASP), 80, 184
Mouschovias, T. Ch. 1996, in *Solar and Astrophysical Magnetohydrodynamic Flows*, ed. K. Tsiganos (Dordrecht: Kluwer), 505
Mouschovias, T. Ch., & Ciolek, G. E. 1999, in *The Origin of Stars and Planetary Systems*, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 305
Mouschovias, T. Ch., & Morton, S. A. 1985a, ApJ, 298, 190
Mouschovias, T. Ch., & Morton, S. A. 1985b, ApJ, 298, 205
Mouschovias T. Ch., & Psaltis D. 1995, ApJ, 444, L105
Mouschovias, T. Ch., Shu, F. H., & Woodward, P. R. 1974, A&A, 33, 73
Mouschovias, T. Ch., & Spitzer, L., Jr. 1976, ApJ, 210, 326
Myers, P. C. 1983, ApJ, 270, 105
Myers, P. C., & Gammie, C. F. 1999, ApJ, 522, L141
Myers, P. C., & Goodman, A. A. 1988, ApJ, 326, L27
Ossenkopf, V., & Mac Low, M.-M. 2002, A& A, 390, 307
Ostriker, E. C., Gammie, C. F., & Stone, J. M. 1999, ApJ, 513, 259
Ostriker, E. C., Stone, J. M., & Gammie, C. F. 2001, ApJ, 546, 980
Padoan, P., & Nordlund, A. 1999, ApJ, 526, 279
Rand, R. J., & Kulkarni, S. R. 1990, ApJ, 349, L43
Roberts, M. S. 1967, IAUS, 31, 189
Roberts, W. W. 1967, ApJ, 158, 123
Rots, A. H. 1975, A&A, 45, 43
Sandage, A., & Tamman, G. A. 1975, ApJ, 196, 313
Schleuning, D. A. 1998, ApJ, 493, 811
Scoville, N. Z., & Solomon, P. M. 1974, ApJ, 187, L67
Scoville, N. Z., Solomon, P. M., & Sanders, D.B. 1979, IAUS, 84, 277
Shu, F. H. 1973, in IAU Symp. 52, *Interstellar Dust and Related Topics*, ed. J. M. Greenberg & H. C. van de Hulst (Dordrecht: Reidel), 257
Shu, F. H. 1977, ApJ, 214, 488
Solomon, P. M, Sanders, D. B., & Scoville, N. Z. 1979, IAUS, 84, 35
Stone, J. M., Ostriker, E. C., & Gammie, C. F. 1998, ApJ, 508, L99
Sung, H., Bessell, M. S., & Lee, S.-W. 1998, AJ, 115, 734
Tassis K., & Mouschovias T. Ch. 2004, ApJ, 616, 283
Vázquez-Semadeni, E., Kim, J., Shadmehri, M., & Ballesteros-Paredes, J. 2005, ApJ, 618, 344
Vogel, S. N., Kulkarni, S.R. & Scoville, N.Z. 1988, Nature, 334, 402
Vrba, F. J., Coyne, G. V., & Tapia, S. 1981, ApJ, 243, 489
Ward-Thompson, D., Scott, P. F., Hills, R. E., & Andre, P. 1994, MNRAS, 268, 276
Zuckerman, B., & Evans, N. J. 1974, ApJ, 192, L152
Zuckerman, B., & Palmer, P. 1974, ARA&A, 12, 279
Zweibel, E. G., & Josafatsson, K. 1983, ApJ, 270, 511